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JAN 62 R A SUTHERLAND, D W HOOK

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**AN IMPROVED SMOKE OBSCURATION MODEL ACT II:  
PART 1 THEORY**

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JANUARY 1982

By

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**Atmospheric Sciences Laboratory**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  This report describes the theoretical basis for the smoke obscuration model ACT II. The work encompasses analytical procedures for determining smoke concentration, temperature, path integrated concentration, path radiance, path luminance, target and background radiance, target-background luminance, and contrast transmission. The model includes both single scattering and thermal		

20. ABSTRACT (cont)

emission and is applicable for wavelengths from the visible through the infrared. Data from Smoke Week II are used to present an example of input/output.

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## 1. INTRODUCTION

The Army inventory contains several models which compute transmission (T) through an obscuring medium composed, for example, of smoke or dust;<sup>1</sup> that is,

$$T = e^{-\tau}, \quad (1)$$

where  $\tau$  is the optical depth along the path of propagation.

On one hand attempts are then made to directly relate transmission to electro-optical system performance and smoke effectiveness by considering only the directly transmitted signal:

$$S(\vec{r}) = S(\vec{r}_0)T, \quad (2)$$

where  $S(\vec{r})$  is the optical signal received by an observer at  $(\vec{r})$  from a target at  $\vec{r}_0$ . The transmission (T) includes effects of both scattering out of the path plus absorption along the path, the composite process being referred to as extinction.

On the other hand system performance modelers know that electro-optical systems (including the eye-brain) respond not only to directly transmitted radiation but also to contrast, the definition of which may vary among models but generally requires an addition to equation (2) to account for path radiance, or "brightness." That is (see also figure 1),

$$S(\vec{r}) = S(\vec{r}_0)T + S_p(\vec{r}), \quad (3)$$

where the contribution due to path radiance ( $S_p$ ) may be due either to scattering of ambient radiation (for example, sun, moon, and sky) into the path of propagation or (thermal) emission along the path, or both. References to scattering out of and into are emphasized to note that the former does not directly contribute to path radiance and can usually be treated as indistinguishable from simple Beer's law attenuation. The latter however, which does contribute to path radiance, is usually a complex function of many factors, including angular properties of both the scattering medium and the ambient radiation.

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<sup>1</sup>R. A. Sutherland, D. W. Hooch, and R. B. Gomez, 1981, An Objective Summary of US Army Electro-Optical Modeling and Field Testing in an Obscuration Environment, ASL-TR-0096, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

Note that, unlike transmission, path radiance has a vector nature which means physically that in real world scenarios, such as the smoked battlefield, asymmetries exist between target and observer, giving one or the other an "optical advantage." This vector nature is the essence of the present model and should not be overlooked in the deceptively simple form of equation (3) or by the necessarily complex formulation to follow.

The existence of path radiance in real world scenarios is often of overriding significance in affecting perception and is commonly observed in nature. One example is the apparent disappearance of stars in daytime. Another is experienced by individuals driving a vehicle through fog with the headlights on high beam. In both cases perception is diminished due to interference caused by scattering that is manifested by path radiance. In the infrared the effect of path radiance is to (partially) offset the effects of absorption. Another example is radiance data sensed via orbiting satellites. Often such data are highly accurate ( $\sim 1^\circ\text{C}$ )<sup>2 3</sup> when inverted to obtain surface temperature. This accuracy occurs despite the fact that the path transmission in these cases, even in the so-called atmospheric "windows," is only on the order of 60 percent, which if taken alone would imply a corresponding temperature error on the order of 50 to 100°C! The explanation here lies in the basic physics of infrared propagation in which, for practical scenarios, absorption is always accompanied by Kirchhoff (i.e., thermal) emission as elucidated for the case of the atmosphere in early works.<sup>4 5</sup>

The degree to which scattering and/or emission can be important is indicated by the optical properties of the medium; the best indicators are the mass extinction coefficient ( $\alpha$ ) which influences total extinction, the single scattering albedo ( $\tilde{\omega}_0$ ) which indicates the fractional amount of scattering, and  $1 - \tilde{\omega}_0$  which indicates the fractional amount of absorption.

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<sup>2</sup>R. A. Sutherland et al, 1979, "A Real Time Satellite Data Acquisition, Analysis and Display System-A Practical Application of the GOES Network," J Appl Meteorol, 3:355-360

<sup>3</sup>E. Chen et al, 1979, "Satellite-Sensed Winter Nocturnal Temperature Patterns of the Everglades Agricultural Area," J Appl Meteorol, 8:992-1002

<sup>4</sup>C. D. Kern, 1965, "Evaluation of Infrared Emission of Clouds and Ground as Measured by Weather Satellites," Environmental Research Papers, No. 155, AFCRL-65-840, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, MA

<sup>5</sup>S. M. Greenfield and W. W. Kellogg, 1960, "Calculations of Atmospheric Infrared Radiation as seen from a Meteorological Satellite," J Meteorol, 6:283-290

Inventory smokes have  $\tilde{\omega}_0 \approx 1$  in the visible,<sup>6</sup> indicating a predominance of scattering, and  $\tilde{\omega}_0 \approx 0$  in the infrared, indicating a predominance of absorption, and consequently emission. Thus path radiance is important and perhaps even of overriding significance for inventory smokes from the visible through the infrared.

The need for further model development in this area was established in an earlier study<sup>1</sup> which made a detailed examination of the Army inventory of existing smoke and dust obscuration models. A major finding of this work was that although most models reported capabilities for treating attenuation, all were deficient in wholly treating path radiance for wavelengths through the infrared.

As a step toward filling this technological gap, an improved smoke obscuration model reported herein was developed. Since three of the models studied (SOM II,<sup>7</sup> HECSOM,<sup>8</sup> and ACT-I,<sup>9</sup> did report some capabilities in the visible, the most promising, ACT-I,\* was chosen as a starting point (hence the acronym ACT-II for the present model).

The approach is to provide optical information critical to the needs of presently existing electro-optical system performance and smoke effectiveness models. An informal survey disclosed that the requirements were reducible to the following fundamental quantities:

1. Ambient irradiance (light level),
2. Target and background radiance,

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<sup>6</sup>R. C. Shirkey and R. A. Sutherland, 1981, "Aerosol Phase Function Data Base," chapter 16, EOSAEL 80, Volume I, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B055130L)

<sup>1</sup>R. A. Sutherland, D. W. Hoock, and R. B. Gomez, 1981, An Objective Summary of US Army Electro-Optical Modeling and Field Testing in an Obscurant Environment, ASL-TR-0096, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

<sup>7</sup>Smoke Obscuration Model II (SOM II) Computer Code Volume II - Analyst Manual, 1979, JTCG/ME Smoke and Aerosol Working Group Document 61, JTCG/ME-78-9-2

<sup>8</sup>R. K. Dumbauld and H. Bjorklund, 1977, Mixing Layer Analysis Routine and Transport/Diffusion Application Routine for EPAMS, ECOM-77-2, Atmospheric Sciences Laboratory, US Army Electronics Command, White Sands Missile Range, NM

<sup>9</sup>R. B. Gomez, R. Pennsyle, and D. Stadtlander, 1979, "Battlefield Obscuration Model, ACT I," Proceedings of Smoke Symposium III, Harry Diamond Laboratories, Adelphi, MD

\*The acronym ACT derives from the developing agencies Atmospheric Sciences Laboratory, Chemical Systems Laboratory, and TRASANA.

3. Line of sight (LOS) transmission, and

4. LOS path radiance,

where target and background radiances are computed for both the unperturbed (smoke free) and smoked environment, and LOS data are provided for both the observer-target and observer-background. From these fundamental quantities other specialized data such as contrast or apparent resolvable temperature can be determined easily for input to existing system performance and smoke effectiveness models such as the target acquisition model of the Night Vision and Electro-Optics Laboratory<sup>10</sup> or the munition expenditures models described by Pennsyle<sup>11</sup> and Hoock.<sup>12</sup>

In another respect care is taken so that the (present) model inputs are compatible with the outputs of other associated models such as LOWTRAN<sup>13</sup> and AGAUS<sup>14</sup> as well as with data collected during field tests such as Smoke Week II.<sup>15</sup>

Although the primary focus is on optical phenomena, the important aspect of obscurant transport and diffusion has not been ignored. The approach here is to generalize procedures so that the model will accommodate any arbitrary ensemble of Gaussian smoke clouds, providing a convenient framework for possible future union with equivalent generalized transport and diffusion models. Most present models, however, do not provide cloud temperature which is critical for the infrared. Thus a Gaussian diffusion model was developed based

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<sup>10</sup>"Combat Simulation Target Acquisition Model and Data Input" (U), CONFIDENTIAL, 1980, Draft Technical Report, US Army Night Vision and Electro-Optics Laboratory, Fort Belvoir, VA (in process)

<sup>11</sup>R. O. Pennsyle, 1979, Methodology for Estimating Smoke/Obscurant Munition Expenditure Requirements, ARCSL-TR-79022, Chemical Systems Laboratory, Aberdeen Proving Ground, MD

<sup>12</sup>D. W. Hoock, 1981, "SCREEN," chapter 5, EDSAEL 80, Volume 1, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B055130L)

<sup>13</sup>J. E. Selby et al, 1978, "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4," Environmental Research Papers, No. 626, AFGL-TR-78-0053, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA

<sup>14</sup>R. C. Shirkey et al, 1980, Single Scattering Code AGAUSX: Theory, Applications, Comparisons, and Listing, ASL-TR-0062, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

<sup>15</sup>DPG Final Test Report on Smoke Week II at Eglin AFB, FL (U), CONFIDENTIAL, 1978, Volumes I and II, DPG-FR-78-317, Dugway Proving Ground, UT

upon commonly used procedures<sup>16 17</sup> and extended to include buoyant rise and cloud temperature using fundamental principles.<sup>18 19</sup>

The work is divided into three parts: the present work covers theory and examples, a second<sup>20</sup> covers program documentation and a users guide, and a third<sup>21</sup> covers validation and applications.

Historically the problem of path radiance and its significance to visible perception have been recognized by the Army modeling community for several years. As early as 1972 an unpublished document described a smoke obscuration model (SOM) which reported to compute visible contrast and was later accepted as the Joint Technical Coordinating Group (JTCG) working model. This early model was expanded by at least two groups, one leading to the development of the model SOM II<sup>7</sup> and another to ASLSOM which was further modified to become the ACT model<sup>9</sup> which is the direct forerunner of the present model.

## 2. OUTLINE AND SCOPE

The fundamental optical quantities to be determined in addition to transmission are the amounts of radiant energy received by an observer from the two directions (approximately coincident) defined by the relative positions of a

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<sup>16</sup>Smoke Effectiveness Manual, 1979, JTCG/ME Smoke and Aerosol Working Group Document Number FM 101-61-8

<sup>17</sup>F. V. Hansen, 1979, Engineering Estimates for the Calculation of Atmospheric Dispersion Coefficients, ASL Internal Report, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

<sup>18</sup>F. Pasquill, 1974, Atmospheric Diffusion, second edition, Halsted Press Div., John Wiley and Sons, Inc., New York

<sup>19</sup>C. H. B. Priestley, 1956, "A Working Theory of the Bent-Over Plume of Hot Gas," Quart J Roy Meteorol Soc, 82:165-176

<sup>20</sup>R. A. Sutherland and D. Clayton, 1981, An Improved Smoke Obscuration Model Act II: Part 2 Documentation and User Guide, Technical Report, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (in process)

<sup>21</sup>R. A. Sutherland, 1981, "Comparisons Between the Improved Smoke Obscuration Model ACT II and Recent Smoke Week Data," Proceedings of Smoke Symposium V, Harry Diamond Laboratories, Adelphi, MD

<sup>7</sup>Smoke Obscuration Model II (SOM II) Computer Code Volume II - Analyst Manual, 1979, JTCG/ME Smoke and Aerosol Working Group Document 61, JTCG/ME-78-9-2

<sup>9</sup>R. B. Gomez, R. Pennsyle, and D. Stadlander, 1979, "Battlefield Obscuration Model, ACT I," Proceedings of Smoke Symposium III, Harry Diamond Laboratories, Adelphi, MD

target and background, both treated as Lambertian surfaces. The radiance incident at the observer from each direction is generally composed of two parts: (1) the direct radiance emitted and reflected by the target (or background) then transmitted (with some loss due to extinction) along the LOS to the observer and (2) the diffuse, or path, radiance emitted and scattered by suspended material (smoke) at all points (such as P in figure 2) along the LOS then transmitted (again with some loss due to extinction) a remaining distance to the observer, giving rise to a path radiance. One aspect of the problem which causes major complexity is that the entire environmental sphere must be considered the source for the reflected and diffuse radiation, thus requiring integration over all angles, not only at the target and background but also at all points along the LOS. Except for rare circumstances, these integrations must be carried out by some approximate numerical technique. The approach taken here is to divide the sky hemisphere into discrete angular sectors and then assume that the radiances from the various sectors are either known from measurement (as in recent field tests) or produced by some appropriate model (perhaps LOWTRAN<sup>13</sup>). Terrain radiance due to reflected sky radiation and thermal emission can then be calculated from knowledge of surface albedo, emissivity, and temperature to complete the characterization of the (smoke free) radiation environment, which is then assumed constant throughout. The exact sectoring procedure used in the model is outlined in section 3.

Mathematically the problem can be summarized by the following formal expression describing radiant propagation along a straight path over a distance  $r$ .<sup>22</sup>

$$R(\vec{r}) = R(\vec{r}_0)e^{-\tau(\vec{r}, \vec{r}_0)} + \int_{\vec{r}_0}^{\vec{r}} [J(\vec{r}', \theta, \phi) + (1 - \tilde{\omega}_0)B(\lambda, T_p)] e^{-\tau(\vec{r}, \vec{r}')} \frac{d\tau}{dr} d\vec{r}' \quad (4)$$

where  $R(\vec{r})$  is the radiance incident at  $\vec{r}$ ;  $R(\vec{r}_0)$  is the radiance of the target (or background) located at  $\vec{r}_0$ ; and  $\theta, \phi$  are the polar angles defining the path of propagation (that is, the LOS). Although the vector notation will be dropped, it is assumed here and in the following that the observer is at the origin and that the coordinates are rotated so that  $\vec{r}$  and  $\vec{r}'$  lie along the LOS (figure 4). Generally the term  $J(r, \theta, \phi)$  (called the source function) accounts for scattering into the LOS, and  $(1 - \tilde{\omega}_0)B(\lambda, T_p)$  accounts for emission from increments along the LOS.

<sup>13</sup>J. E. Selby et al, 1978, "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4," Environmental Research Papers, No. 626, AFGL-TR-78-0053, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA

<sup>22</sup>S. Chandrasekhar, 1960, Radiative Transfer, second edition, Dover Press Publications, Inc., New York

The Planck or blackbody function of equation (4) is written explicitly as

$$B(\lambda, T_p) = \frac{2hc^2 \lambda^{-5} \Delta\lambda}{[\exp(hc/kT_p) - 1]} \quad (5)$$

where  $\lambda$  is the wavelength,  $\Delta\lambda$  the bandpass, and  $h$ ,  $k$ , and  $c$  are, respectively, the Planck constant, the Boltzmann constant, and the speed of light in vacuum. The obscurant temperature ( $T_p$ ) is assumed variable over the path, so that  $B$  contains an implicit dependence on  $r$ .

The optical thickness ( $\tau$ ) is defined as

$$\tau(r, r') = \int_{r'}^r \alpha C(r'') dr'' , \quad (6)$$

where  $\alpha$  is the obscurant mass extinction coefficient and  $C$  is the obscurant concentration. Both obscurant temperature and concentration are discussed in section 5.

The source function  $J(r, \theta, \phi)$  is difficult to compute, requiring integrations over the entire environmental sphere accounting for the angular characteristics of both the ambient radiation and the scattering medium. Except for trivial cases, no exact methods exist for computing this term; and for realistic scenarios, some approximate technique must be employed. The model uses the single scattering approximation in which the source function can be written as

$$J(r, \theta, \phi) = \frac{1}{4\pi} \int_{4\pi} P(\theta_s) L(\theta', \phi') e^{-\tau(r, r_s)} d\Omega' , \quad (7)$$

where  $\theta_s$  is the scattering angle (figure 2) and  $P$  the phase function. The term  $L(\theta', \phi')$  consists of two parts: the source radiance  $R_s(\theta', \phi')$  from the directions of the sky and terrain sectors and the thermal emission along these same directions. Mathematically,

$$L(\theta', \phi') = R_s(\theta', \phi') + (1 - \tilde{\omega}_0) \int_r^{r_s} B(\lambda, T_p) e^{[\tau(r, r_s) - \tau(r, r')]} dr' . \quad (8)$$

In the above expressions,  $r$  is distance to any point along the LOS;  $r'$  is distance from that point along the direction defined by  $\theta'$ ,  $\phi'$ ;  $r_s$  is distance to the sky and terrain sources; and  $d\Omega'$  is the differential solid angle.

For inventory smokes (and neglecting polarization), the angular dependence of the phase function is dependent only upon the scattering angle, which from simple geometry is given by (see figure 2):

$$\cos \theta_s = [\cos \theta \cos \theta' + \sin \theta \sin \theta' \cos(\phi - \phi')] . \quad (9)$$

Some caution is required in using equation (9) to assure the proper algebraic sign. For use in the phase function equation (9) is correct as it stands, but for Lambertian surfaces (that is, target, background, etc.) the sign must be reversed because the convention used in the model requires the surface normal pointing positive inward (for example, away from the observer) which in turn requires the reversal in sign.

The phase function is required as input but can readily be obtained from the associated model AGAUS,<sup>14</sup> one version of which is distributed with the Electro-Optical Systems Atmospheric Effects Library (EOSAEL 80<sup>23</sup>). The phase function is assumed to be normalized such that

$$\frac{1}{4\pi} \int_{4\pi} P(\theta_s) d\Omega = \tilde{\omega}_0 , \quad (10)$$

but in the model it is renormalized via equation (10) to a single scattering albedo specified as input. However, to be strictly compatible with theory the input single scattering albedo should be that computed from Mie scattering.

The major objective of the model is to evaluate the two components of equation (4), once for the observer-target and once for the observer-background by using the procedures described by equations (4) through (9). For the special case of computing  $R(r_0)$ , the target or background radiance, the same procedure for the second term of equation (4) is used except that the factor  $\frac{1}{4\pi} P(\theta_s)$  in equation (7) is replaced by  $(a \cos \theta_s / \pi)$  which assumes a Lambertian surface of albedo\* (a) with surface normal along the LOS. Also for these cases the computations are restricted to  $\theta_s > 90^\circ$  to avoid contributions due to reflection from the rear surface. The  $(\text{smoke free})$  surface irradiance ( $E_{\text{sfc}}$ ) is also computed in the same manner with  $\theta = \phi = 0$  (vertical) and the factor  $1/\pi$

<sup>14</sup>R. C. Shirkey et al, 1980, Single Scattering Code AGAUSX: Theory, Applications, Comparisons, and Listing, ASL-TR-0062, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

<sup>23</sup>R. A. Sutherland, 1981, "Smoke Obscuration Model," chapter 3, EOSAEL 80, Volume 1, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B055130L)

\*For opaque surfaces, reflectivity (r), albedo (a), and emissivity (ε) are related as (a = r and ε = 1 - r).

removed. In all cases, an emission term of the form  $\epsilon B(\lambda, T)$  is added where  $T$  is chosen appropriately as the surface, target, or background temperature, and the emissivity ( $\epsilon$ ) is computed from the reflectivity or albedo as  $\epsilon = (1 - a)$ . The (smoke free) surface irradiance is used later (see equation (18)) to compute radiances for terrain sectors which are then treated in the same manner as sky sectors.

For the visible scenarios, the effect of emission will be negligible because of the smallness of the blackbody function in these spectral regions at nominal temperatures. For infrared scenarios, this term often dominates, being more pronounced at higher temperature, which means that errors due to neglect of multiple scattering will be minimal in the infrared. However, errors may occur in the infrared due to uncertainties in the cloud temperature.

The process to be modeled here can be summarized in geometrical terms with the aid of figure 2. Simply stated, the problem is to compute contributions to path radiance at each point  $P$  along the LOS, and then to sum over all such points. At each increment, effects of extinction must be included over the remaining path  $\overline{PO}$  to the observer. At each point  $P$  the contribution is composed of two parts--one due to scattering into the increment from all angles and the other due to emission by the increment. The single scattering approximation assumes that the radiance along any path  $\overline{SP}$  is scattered into the LOS only once and that this scattering occurs at  $P$ . Thus the radiance scattered into the LOS at point  $P$  consists of the source radiance,  $R_s$ , reduced by extinction over the path  $\overline{SP}$ , plus the summation of the emission from each element  $P'$  along the path  $\overline{SP}$ ; the emissive contribution of each element is reduced by extinction over the path  $\overline{PP'}$ . The total scattering contribution of each increment at  $P$  is found by summing over all angles, accounting for angular scattering properties of the medium via the phase function. Total path radiance is found by summing over all increments along  $\overline{OT}$ .

In the model the increment spacings are chosen by a criterion based upon the incremental optical depth  $\Delta\tau$ . This method speeds computations by avoiding insignificant contributions for increments containing no obscurant which would occur for a criterion based on spatial separation ( $\Delta r$ ). The minimum spacing in the model however is normally defaulted to 1 m.

The model treats extinction due to the ambient atmosphere by appropriately modifying transmission (i.e.,  $T_{LOS} = T_{smoke} T_{atmos}$ ) for propagation along the LOS. This option is employed by way of a user supplied volume extinction coefficient, ( $\sigma$ ), so that  $T_{atmos} = e^{-\sigma L}$ , where  $L$  is distance of propagation. Parallel point sources of radiation, including the sun or moon, are also treated by the model.

In all of the above computations, the model computes optical thickness ( $\tau$ ) by assuming the medium composed of any ensemble of obscuring smoke clouds defined by centroid locations, Gaussian standard deviations, and temperature. Methods for integrating equation (6) and for producing the ensemble are given in later sections of the report.

### 3. AMBIENT IRRADIANCE (SECTORING SCHEME)

This section describes the sectoring scheme used to simulate incoming radiation from sky and terrain which will then be used to approximate terms for the source function of equation (8). Throughout this section repeated use will be made of approximations, assuming that scenario relative distances are small in comparison to spatial variations in ambient conditions. This process considerably simplifies the geometry by allowing all scenario elements to be treated as exposed to the same ambient radiational environment. These are approximations often used in problems of this type and introduce only minimal errors.

The major divisions of the entire  $4\pi$  steradians comprising the environmental sphere are sketched in figure 3. The upper sector is assumed to be comprised of sky (including sun, moon, and clouds) and the lower to be overall flat terrain. Both sky and terrain will be treated as sources of ambient radiation, the latter through reflection of sky radiation and thermal emission.

To facilitate computations, the two major regimes are further subdivided into angular sectors subtending equal solid angles. These discrete sectors are then treated as point sources of parallel radiation emanating from the direction of the sector midpoint. Additional sources of radiation such as the sun or moon are superimposed at their appropriate angular positions. The model will accommodate variable radiance from each of the discrete sky sectors, but to maintain consistency with the assumptions mentioned earlier, one must assume that the terrain is homogeneous in albedo, emissivity, and temperature.

The procedure for sectoring the two regimes into equal angular sectors follows directly from the definition of solid angle;  $d\Omega_{\theta, \phi} = \sin \theta d\theta d\phi$ , where  $\theta$  and  $\phi$  are the usual zenith and azimuth angles.

The azimuthal sectoring is particularly simple since integration over contiguous divisions  $(\phi_i, \phi_{i+1})$  yields, simply,  $d\Omega_{\theta} = \Delta\phi \sin \theta d\theta$ , where  $\Delta\phi = \phi_{i+1} - \phi_i$  is the azimuthal separation, which for  $m$  sectors is simply  $\Delta\phi = 2\pi/m$ . The representative midpoints are then

$$\phi_i = (i - 1)\pi/m . \quad (11)$$

For the zenith sectors, the integration between contiguous divisions yields

$$\Delta\Omega = \Delta\phi(\cos \theta_j - \cos \theta_{j+1}) . \quad (12)$$

For  $n$  sectors, all of which are equal and contained in a total solid angle  $2\pi$ , we have

$$\Delta\phi(\cos \theta_j - \cos \theta_{j+1}) = 2\pi/nm , \quad (13)$$

which after substituting for  $\Delta\phi$  and rearranging becomes

$$\cos \theta_{j+1} = \cos \theta_j - 1/n , \quad (14)$$

from which all divisions can be calculated by knowing that  $\theta_1 = 0$ . An equivalent but sometimes more convenient expression is

$$\cos \theta_j = 1 - (j - 1)/n . \quad (15)$$

Further reasoning yields the following equation for sector midpoints:

$$\cos \bar{\theta}_j = 1 - (2j - 1)/2n . \quad (16)$$

The corresponding distances to the terrain sector midpoints are

$$r_s^{i,j} = h/\cos \bar{\theta}_j , \quad (17)$$

where  $h$  is the vertical distance from the surface for the particular scenario element under consideration. The radiance from the sector, assuming a Lambertian surface is

$$R = [(a/\pi)E_{sfc} + (1 - a)B(\lambda, T_{sfc})] , \quad (18)$$

where  $a$ ,  $E_{sfc}$ , and  $T_{sfc}$  are, respectively, the surface albedo, irradiance (see section 2), and temperature. From this point on, the only difference in treating sky or terrain sectors is that the finite distance to the terrain sectors must be considered via equation (17), whereas the sky sectors can be assumed at infinity (actually 10,000 m in the model).

Ordinarily one does not have sufficient data, or the inclination, to provide the radiance values for all of the sectors used in the model; therefore, the model was programmed to proportion the sectors uniformly by interpolating the input radiance values from arbitrary angles. This interpolation makes the model input directly compatible with sky radiance data from the smoke tests.

Also, to avoid inconsistencies between the computed surface irradiance ( $E_{sfc}$ ) and the reported measurements,<sup>21</sup> the sun and sky input data are treated only as relative and are normalized so as to reproduce the measured value when integrated over the sky hemisphere. Thus the model as now coded requires only relative data from sun and sky but an absolute determination of surface irradiance. In effect this method reduces the complexity of the required input.

#### 4. OPTICAL THICKNESS CALCULATIONS

This section describes the general method used to compute smoke concentration  $C(r)$  and optical thickness. Throughout we will assume a constant extinction coefficient so that the optical depth is simply the product ( $\alpha CL$ ) where  $CL$  is the line integrated concentration, commonly called  $CL$  product.

The methodology is based upon the general assumption that a smoke plume or cluster can be represented by a series of spatially and temporally discrete overlapping clouds each with concentration given by a trivariant Gaussian function. This is a common assumption used in many models although the manner of spacing and sizing such clouds may vary from model to model. For this latter reason the methodology is kept general so as to be easily adaptable to various cloud transport models.

For some  $i^{th}$  cloud centered at  $\bar{X}_i$ ,  $\bar{Y}_i$ , and  $\bar{Z}_i$  the concentration (due to this source only) is given by

$$C_i(x, y, z) = (2\pi)^{-3/2} \frac{Q_i}{\sigma_x^i \sigma_y^i \sigma_z^i} e^{-1/2 \left[ \left( \frac{x - \bar{X}_i}{\sigma_x^i} \right)^2 + \left( \frac{y - \bar{Y}_i}{\sigma_y^i} \right)^2 + \left( \frac{z - \bar{Z}_i}{\sigma_z^i} \right)^2 \right]} \quad (19)$$

where  $Q_i$  is the total mass of the cloud and accounts for (1) munition fill mass expended during the burn producing the cloud, (2) munition efficiency, and (3) smoke yield factor. The total concentration is found by summing the concentrations of all such clouds.

<sup>21</sup>R. A. Sutherland, 1981, "Comparisons Between the Improved Smoke Obscuration Model ACT II and Recent Smoke Week Data," Proceedings of Smoke Symposium V, Harry Diamond Laboratories, Adelphi, MD

It is convenient to rewrite equation (19) in spherical coordinates to give an expression for concentration along an LOS defined as before by polar angles  $\theta$  and  $\phi$  at some arbitrary point a distance  $r$  from the origin. It is straightforward to show that the equivalent to equation (19) is

$$C(r, \theta, \phi) = \frac{(2\pi)^{-3/2} Q}{\sigma_x \sigma_y \sigma_z} e^{-1/2} \left[ \left( \frac{\alpha r - x_0}{\sigma_x} \right)^2 + \left( \frac{\beta r - y_0}{\sigma_y} \right)^2 + \left( \frac{\gamma r - z_0}{\sigma_z} \right)^2 \right] \quad (20)$$

where the indices have been dropped to avoid cumbersome notation. The line parameters  $\alpha$ ,  $\beta$ ,  $\gamma$  and offsets  $x_0$ ,  $y_0$ ,  $z_0$  are:

$$\begin{aligned} \alpha &= \sin \theta \sin \phi & x_0 &= \bar{X}_i - x_1 \\ \beta &= \sin \theta \cos \phi & y_0 &= \bar{Y}_i - y_1 \\ r &= \cos \theta & z_0 &= \bar{Z}_i - z_1 \end{aligned} \quad (21)$$

where  $x_1$ ,  $y_1$ , and  $z_1$  are coordinates of any point on the LOS, taken in the model to be the common point such as P in figure 4.

With considerably more algebraic manipulation which involves expanding the expression in the exponential, rearranging and then rewriting the resultant expression as a perfect square, the following expression results:

$$C_i(r, \theta, \phi) = Q_i' e^{-1/2} \left( \frac{r - \bar{R}_i}{\Sigma_i} \right)^2 \quad (22)$$

which is itself a Gaussian with mean  $\bar{R}_i$ , standard deviation  $\Sigma_i$ , and strength  $Q_i'$  given by the following expressions, again with indices suppressed:

$$\begin{aligned} \bar{R} &= \frac{\alpha x_0 (\sigma_z \sigma_y)^2 + \beta y_0 (\sigma_x \sigma_z)^2 + \gamma z_0 (\sigma_x \sigma_y)^2}{(\alpha \sigma_y \sigma_z)^2 + (\beta \sigma_x \sigma_z)^2 + (\gamma \sigma_x \sigma_y)^2} \\ \Sigma &= \frac{\sigma_x \sigma_y \sigma_z}{[(\alpha \sigma_y \sigma_z)^2 + (\beta \sigma_x \sigma_z)^2 + (\gamma \sigma_x \sigma_y)^2]^{1/2}} \end{aligned} \quad (23)$$

$$Q' = \frac{(2\pi)^{-3/2} Q}{\sigma_x \sigma_y \sigma_z} e^{-1/2} \left[ R_\sigma - \left( \frac{\bar{R}}{\bar{\Sigma}} \right)^2 \right]$$

$$R_\sigma = \left( \frac{x_0}{\sigma_x} \right)^2 + \left( \frac{y_0}{\sigma_y} \right)^2 + \left( \frac{z_0}{\sigma_z} \right)^2$$

(23) cont

The final desired result for line integrated concentration beginning at point  $P(x_1, y_1, z_1)$  along the line described by  $(\alpha, \beta, \gamma)$  for a distance  $D$  becomes (see figure 4):

$$CL_i(D, \theta, \phi) \sqrt{\pi/2} = Q'_i \Sigma_i \left[ \operatorname{erf} \left( \frac{D - R_i}{\sqrt{2\Sigma_i}} \right) + \operatorname{erf} \left( \frac{R_i}{\sqrt{2\Sigma_i}} \right) \right] \quad (24)$$

where the error function is defined as

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt \quad (25)$$

and is computed in the model according to the approximate technique as described by Abramowitz and Stegun.<sup>24</sup>

The formulation here applies in a wind vector aligned coordinate system requiring that scenario Cartesian coordinates and angles be transformed to this system before the calculations.

The model assumes both concentration and temperature to be Gaussian so that a relationship analogous to equation (24) is used to obtain temperature of various line segments for computation of thermal emission. Also symmetric "image" clouds accounting for surface particulate reflection are included in the usual manner.<sup>23</sup>

## 5. CLOUD CONCENTRATION AND TEMPERATURE

The preceding sections assumed a transport and diffusion model generating some pattern of overlapping Gaussian clouds. Several methodologies which can be

<sup>24</sup>M. Abramowitz and I. Stegun, 1970, Handbook of Mathematical Functions, Dover Press Publications, Inc., New York

<sup>23</sup>R. A. Sutherland, 1981, "Smoke Obscuration Model," chapter 3, EOSAEL 80, Volume 1, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B05513JL)

adapted to this general concept are available. We borrow bits and pieces from these methodologies to produce a submodel to be used for the validation studies reported later. Production of this model consists of generating the parameters  $Q_i$ ,  $(\bar{X}_i, \bar{Y}_i, \bar{Z}_i)$ ,  $(\sigma_x^i, \sigma_y^i, \sigma_z^i)$ , and cloud temperature which will now be covered in order.

### 5.1 Smoke Source Function (Q)

The factor Q represents the total mass of a smoke cloud and is composed of the product of factors M,  $\lambda$ , and Y where M is the mass of munition fill expended during the burn producing the cloud,  $\lambda$  is the chemical efficiency with which the mass is converted to actual smoke nuclei, and Y is the smoke yield factor which accounts for increased mass due to hygroscopic interactions with the ambient air mass.

For instantaneous bursts such as bulk fill white phosphorus munitions, a single cloud of mass  $Q = M \lambda Y$  is used. For munitions of extended burning time ( $> 1$  s), the plume is generated as a series of discrete puffs produced during short time increments (nominally 1 s). Variable burn rate is included by employing either a quadratic or exponential function with coefficients as determined empirically from field tests. The EOSAEL 80 Technical Documentation<sup>23</sup> contains a review of these burn coefficients and other munition characteristics.

### 5.2 Cloud Centroids ( $\bar{X}$ , $\bar{Y}$ , and $\bar{Z}$ )

With the coordinate system rotated to align the positive x axis along the wind vector and assuming the cloud to be transported by the mean wind ( $\bar{U}$ ), the cloud centroids are modeled as

$$\begin{aligned}\bar{X} &= \bar{U} + X_m \\ \bar{Y} &= Y_m\end{aligned}\tag{26}$$

$$\bar{Z} = Z_m + H(t)$$

where  $X_m$ ,  $Y_m$ , and  $Z_m$  are munition coordinates. The method of computing the cloud rise function  $H(t)$  which also involves the cloud temperature is discussed later. The mean windspeed is computed by averaging vertically over the

<sup>23</sup>R. A. Sutherland, 1980, "Smoke Obscuration Model," chapter 3, EOSAEL 80, Volume 1, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B055130L)

significant cloud extent ( $3\sigma$ ) using the usual windspeed power law:  $U(z) = U_r(z/z_r)^P$  where  $U_r$  is the windspeed at an (input) reference height ( $Z_r$ ) and  $P$  is the vertical profile exponent.

### 5.3 Dispersion Functions ( $\sigma_x, \sigma_y, \sigma_z$ )

The dispersion functions  $\sigma_x, \sigma_y, \sigma_z$  are all expressed as power functions of the x centroid with initial offset,  $\sigma(0)$ ; that is,

$$\sigma_{x, y, z} = \sigma(0) + \left( \frac{X - C}{A} \right)^B \quad (X \text{ in meters}) \quad (27)$$

The source sigmas  $\sigma(0)$ , essentially representing the dimensions of the cloud at  $t = 0$  are modeled by the following power functions which were derived from the data of AMSAA TR-201.<sup>25</sup>

$$\begin{aligned} \sigma_{x, y}(0) &= 5.0 Q^{0.3} \\ \sigma_z(0) &= 1.7 Q^{0.3} \end{aligned} \quad (Q \text{ in kilograms}) \quad (28)$$

The diffusion parameters  $A$  and  $B$  of equation (27) are modeled as functions of the surface average roughness element ( $Z_0$ ) and the stability category as listed in table 1. For surface roughness  $Z_0 > 0$ , the values are those cited by Hansen;<sup>17</sup> and for these cases the parameter  $C$  of equation (27) is set to zero. For a roughness entered as  $Z_0 < 0$  (default), the method of the Smoke Effectiveness Manual<sup>16</sup> is used, in which case the initial sigmas are absorbed in the parameter  $C$ , and the term  $\sigma(0)$  is set to zero.

<sup>25</sup>Analysis of the Smoke Cloud Data from the August 1975 Jefferson Proving Ground Smoke Test, 1977, AMSAA Technical Report TR-201, Aberdeen Proving Ground, MD (AD A045874)

<sup>17</sup>F. V. Hansen, 1979, Engineering Estimates for the Calculation of Atmospheric Dispersion Coefficients, ASL Internal Report, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

<sup>16</sup>Smoke Effectiveness Manual, 1979, JTCG/ME Smoke and Aerosol Working Group Document Number FM 101-61-8

Following the methodology cited by Hansen,<sup>17</sup>  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$  are reduced by factors 0.74, 0.67, and 0.67, respectively, for instantaneous sources.

#### 5.4 Cloud Temperature and Buoyant Rise

Current methods for modeling buoyant rise are generally limited to empirical methods based upon observations of factory smoke stack effluents<sup>26</sup> or curve fits to data from field tests.<sup>25</sup> These procedures, although of approximate validity for special circumstances, have severe shortcomings for the general case where it becomes necessary to simultaneously model cloud temperature consistently. This consistency is particularly important in the infrared where cloud temperature acquires an added significance of its own in addition to the indirect effect on buoyancy. The method developed for the model applies basic principles and certain simplifying assumptions borrowing heavily from earlier works<sup>18 19</sup> in a self-consistent numerical scheme as outlined below.

The buoyant motion is modeled by treating each cloud of the ensemble as though independent of other clouds, an assumption consistent with the transport and diffusion methodology discussed earlier. Initial cloud temperature is modeled by equating the internal thermal energy of each instantaneous cloud to the energy expended during the exothermal reaction producing the cloud. Assuming, as before, similar distributions in both temperature and concentration, the following expression results for initial cloud temperature:

$$T_c = \frac{E C_o + \rho C_p T_z}{\rho C_p}, \quad (29)$$

where  $E$  is the obscurant heat of reaction (calorie/gram),  $C_o$  the mean concentration,  $\rho C_p$  the volumetric specific heat of the ambient air ( $290 \text{ cal m}^{-3} \text{ } ^\circ\text{C}^{-1}$ ), and  $T_z$  the ambient air temperature at the cloud centroid. The use of equation (29) assumes complete thermal mixing between cloud and entrained air.

<sup>26</sup>G. A. Briggs, 1965, "A Plume Rise Model Compared with Observations," J Air Poll Control Assoc., 15:433

<sup>25</sup>Analysis of the Smoke Cloud Data from the August 1975 Jefferson Proving Ground Smoke Test, 1977, AMSAA Technical Report TR-201, Aberdeen Proving Ground, MD (AD A045874)

<sup>18</sup>F. Pasquill, 1974, Atmospheric Diffusion, second edition, Halsted Press Div., John Wiley and Sons, Inc., New York

<sup>19</sup>C. H. B. Priestley, 1956, "A Working Theory of the Bent-Over Plume of Hot Gas," Quart J Roy Meteorol Soc., 82:165-176

The vertical (ambient) temperature profile is modeled as

$$T_z = T_r + T_0 \frac{1 - \exp[-\alpha(z - z_r)/H_m]}{1 - \exp[-\alpha(H_m - z_r)/H_m]} \quad z \leq H_m/10$$

$$T_z = T_{10} + \left[ \frac{T_{hm} - T_{10}}{H_m - H_m/10} \right] z \quad z > H_m/10 \quad (30)$$

$$T_{10} = T_z(H_m/10) ,$$

where  $T_r$  is the temperature measured at the reference height ( $z_r$ ),  $T_{hm}$  is the temperature at the mixing height ( $H_m$ ), and  $\alpha$  is chosen so as to fit to the measured ambient temperature gradient at the reference height and to the adiabatic lapse rate ( $0.00966^\circ\text{C/m}$ ) at  $z = H_m/10$ .

The vertical velocity ( $\omega$ ) at any later time is found by first applying the conservation of momentum along the vertical:

$$\frac{d\omega}{dt} = \frac{g}{T_z} \Delta T - k_m \omega , \quad (31)$$

where  $\Delta T$  is cloud temperature excess,  $g$  is the acceleration due to gravity,  $T_z$  as before is the (absolute) ambient air temperature at the centroid height, and  $k_m$  is the momentum mixing coefficient taken to be  $0.10 \text{ s}^{-1}$ .<sup>19</sup>

Equation (31) with (29) and (30) is then solved for  $\omega$  using reiterative techniques assuming zero initial velocity to further determine the rise function by way of the following kinematic relations:

$$\omega(t) = \omega(t - \Delta t) + (d\omega/dt)\Delta t;$$

$$H(t) = H(t - \Delta t) + \omega(t)\Delta t . \quad (32)$$

<sup>19</sup>C. H. B. Priestley, 1956, "A Working Theory of the Bent-Over Plume of Hot Gas," Quart J Roy Meteorol Soc, 82:165-176

The process is then repeated by incrementing time (and hence C) over the "age" of the cloud. Beyond the first time increment, a term  $[(\Delta T) \times \Delta C/C]$  is sequentially added to equation (29) to account for the vertically changing temperature of the ambient entrained air. In actual practice the time increment is computed so as to limit the cloud rise increment to 1 m or less to assure convergence of the numerical procedure.

## 6. EXAMPLE (FROM SMOKE WEEK II)

### 6.1 Conversion of Model Results

As mentioned in section 1, the model was coded in such a way as to be compatible with measurements made during the major field tests. This coding allows nearly direct comparison between model results and measured data. However, a word of caution is required to interpret the results appropriately.

The model has assumed radiometric units throughout, whereas the units reported in the field tests are mixed; that is, sky and solar data are in radiometric units, but target, background, and path radiance are in photopic units. Because the underlying spectrum is not uniform (that is, the sky is blue, clouds are white, and the sun is yellow-green), some error and confusion result when converting between the two systems. Rather than try to correct for the nonuniform spectrum (a procedure which could only increase the error), we choose here to assume the spectrum nearly uniform and convert the model results to photopic units by using the standard photopic response curve<sup>27</sup> which can be closely approximated by the following Gaussian function (see figure 5):

$$R_p = R_0 \exp[-1/2(\lambda - \lambda_0)^2/\sigma^2] , \quad (33)$$

where

$$R_0 = 673 \text{ lm/W} ,$$

$$\lambda_0 = 0.56 \mu\text{m} ,$$

$$\sigma = 0.0426 \mu\text{m} ,$$

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<sup>27</sup>A. Stimson, 1974, Photometry and Radiometry for Engineers, John Wiley and Sons, Inc., New York

which can be integrated to yield the following conversion factor:

$$E(lm) = R_0 \sqrt{2\pi} \sigma E(W) , \quad (34)$$

or in terms of bandwidth (full width at half maximum):

$$E(lm) = R_0 \left[ \frac{\pi}{2 \ln 2} \right]^{1/2} \Delta \lambda E(W) . \quad (35)$$

Both the bandwidth ( $\Delta \lambda$ ) and position of maximum response ( $\lambda_0$ ) are input by the user and are  $0.100 \mu m$  and  $0.56 \mu m$  for straight photopic conversion. For input wavelengths other than  $0.56 \mu m$ , the model shifts and reduces the peak response via a multiplicative Gaussian factor:

$$f = \exp \left[ -1/2 \left( \frac{\lambda_i - 0.56}{\sigma} \right)^2 \right] \quad (36)$$

which is equal to unity for  $\lambda = 0.56$  and is essentially zero for the infrared. In all cases the model also provides output in radiometric units.

Also the Smoke Week sun and sky radiances are reported for a detector field of view of  $1^\circ$  requiring division by  $(\pi/180)^2$  to convert to a unit steradian. This conversion is not required for the input to the model as now coded since these data are used only in a relative sense. For sake of completeness, some further required conversion factors are:

$$1 \text{ footcandle} = 10.76 \text{ lumens per square meter}$$

$$1 \text{ footlambert} = \frac{10.76}{\pi} \text{ candles per square meter} \quad (37)$$

$$1 \text{ candle} = 1 \text{ lumen per steradian}$$

## 6.2 Input Data

Trial 1 of the Smoke Week II field test, held at Eglin Air Force Base, Florida, in November 1978 consisted of the detonation of 15 155-mm hexachloroethane (HC) Type M1 canisters arranged in the configuration sketched in figure 6. The source characteristics used in the model were those as reported

in EOSAEL 80 Technical Documentation;<sup>23</sup> and the mass extinction coefficient, single scattering albedo, and phase function were those of Shirkey, Clayton, and Quintis<sup>28</sup> for HC smoke. For modeling purposes, the munitions were separated into four groups as indicated by the sketched outlines in figure 6 with each group treated as single-point detonation of appropriate total mass. For buoyant smokes this latter procedure may cause some concern; however, for HC munitions which are only slightly buoyant this procedure causes only insignificant errors.

Meteorological conditions during the test were typical of fair weather with 30 percent cloud cover and 11.3 km visibility. Model inputs either taken from the original test report or derived (estimated) from data therein are listed in table 2. Table 3 lists the ambient sky radiation measurements made during these tests.

The sky radiance map derived from the data of table 3 for the model sector midpoints is shown in figure 7.

Figure 8 shows the modeled and measured results for both path integrated concentration (figure 8a) and path luminance (figure 8b). The results for path integrated concentration, although overall high, are typical of those reported in other validation studies.<sup>29</sup> The path luminance results are most interesting in that the brightening effect at the cloud edges is quite noticeable. This effect is often observed in natural clouds and is referred to as a "silver lining." The occurrence and magnitude of the bright edges depend strongly upon the angular distribution of ambient radiation. The overall agreement between model data and data of figure 8b is encouraging.

Figure 9 is a more detailed examination of the cloud at time  $t = 100$  s. Here both the direct and diffuse components of radiation are plotted as a function of depth of penetration. This procedure may be viewed as moving the target into the cloud along the LOS away from the observer. Until a significant portion of the cloud is penetrated, the diffuse component is near zero and the

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<sup>23</sup>R. A. Sutherland, 1981, "Smoke Obscuration Model," chapter 3, EOSAEL 80, Volume 1, Technical Documentation, editor L. D. Duncan, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B055130L)

<sup>28</sup>R. C. Shirkey, D. Clayton, and D. M. Quintis, 1981, "Aerosol Phase Function Data File PFNDAT," chapter 16, EOSAEL 80, Volume II, Users Manual, editors R. C. Shirkey and S. G. O'Brien, ASL-TR-0073, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (AD B056119)

<sup>29</sup>D. W. Hoock, R. A. Sutherland, and D. Clayton, 1981, Comparisons Between the EOSAEL 80 Model SMOKE and the Inventory Munition Test Phase IIa, Technical Report, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM (in process)

direct component is at a maximum. As the target moves into the cloud, the diffuse component increases while the direct component decreases. The net effect is a reduction in both the direct signal and the contrast.

A discussion of how these (and other) outputs of the model can be used in other smoke screening and perception models can be found elsewhere.<sup>30</sup>

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<sup>30</sup>D. W. Hoock and R. A. Sutherland, 1981, "Path to Background Luminance Ratios for the EOSAEL 80 Munitions Expenditure Model SCREEN," Proceedings of Smoke Symposium V, Harry Diamond Laboratories, Adelphi, MD

TABLE 1. DIFFUSION PARAMETERS USED IN THE TRANSPORT AND DIFFUSION ROUTINE FOR VARIOUS VALUES OF ROUGHNESS PARAMETER ( $Z_0$ ) AND STABILITY CATEGORY.\*

		STABILITY CATEGORY					
		A	B	C	D	E	F
Default	$A_x$	7.57	7.57	7.57	7.57	7.57	7.57
	$B_x$	0.93	0.93	0.93	0.93	0.93	0.93
	$A_y$	44.1	44.1	44.1	24.8	15.6	15.6
	$B_y$	1.50	1.50	1.50	0.88	0.66	0.66
	$A_z$	16.4	16.4	16.4	14.2	12.7	12.7
	$B_z$	1.50	1.50	1.50	0.88	0.66	0.66
$0 \leq Z_0 < 10$	$A_x$	2.77	3.55	5.38	8.68	12.6	17.5
	$B_x$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_y$	2.77	3.55	5.38	8.68	12.6	17.5
	$B_y$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_z$	7.32	9.65	12.0	15.6	26.3	47.6
	$B_z$	0.94	0.89	0.85	0.81	0.78	0.72
$10 \leq Z_0 < 100$	$A_x$	2.77	3.55	5.38	8.68	12.6	17.55
	$B_x$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_y$	2.77	3.55	5.38	8.68	12.6	17.5
	$B_y$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_z$	4.13	5.78	6.75	8.59	14.9	24.6
	$B_z$	0.90	0.85	0.80	0.76	0.73	0.67
$Z_0 > 100$	$A_x$	2.77	3.55	5.38	8.68	12.6	17.5
	$B_x$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_y$	2.77	3.55	5.38	8.68	12.6	17.5
	$B_y$	0.90	0.90	0.90	0.90	0.90	0.90
	$A_z$	1.80	2.23	2.40	3.17	5.07	7.57
	$B_z$	0.83	0.77	0.72	0.68	0.65	0.58

\* $Z_0$  in centimeters, x, y, and z in meters.

TABLE 2. AMBIENT RADIATION MEASUREMENTS (VISIBLE) FROM SMOKE WEEK 11, TRIAL 1  
FIELD TEST.\*

$\phi \rightarrow$ $\theta \downarrow$	<u>Sky Radiance <math>W \text{ sr}^{-1} \text{ m}^{-2}</math></u>			
	<u>3.7°</u>	<u>70.7°</u>	<u>160.7°</u>	<u>250.7°</u>
0°	6.2	6.2	6.2	6.2
10°	9.8	12.1	15.8	13.1
20°	7.5	13.1	20.7	13.1
30°	6.6	5.1	33.8	13.1
40°	7.5	17.4	54.5	12.1
50°	8.5	19.7	133.6	13.1
60°	10.8	21.3	124.7	13.1
70°	13.1	21.3	124.7	17.4
80°	17.4	10.8	103.4	17.4
90°	18.4	8.9	68.6	18.1

Solar:

Zenith	Azimuth	Beam flux ( $W/m^2$ )
51.5	151.9	208.7

Surface Irradiance ( $W/m^2$ ): 571.5

\*Note that reported sky radiance data must be divided by  $(\pi/180)^2$  to convert unit solid angle to 1 sr. Also a factor  $10^{-2}$  converts  $\mu W/cm^2$  to  $W/m^2$

TABLE 3. METEOROLOGICAL INPUTS TO THE MODEL FOR  
SMOKE WEEK II, TRIAL 1 FIELD TEST

Windspeed (8 m)	4.1 m/s
Wind direction (8 m)	116.3 deg
Wind power law exponent	0.11
Ambient air temperature (1.0 m)	23.6°C
Temperature gradient	-0.36°C/m
Mixing height	400 m (derived in model)
Mixing height temperature	18.3°C (derived in model)
Stability category (Pasquill)	C
Relative humidity	52%
Dew-point temperature	not needed
Surface irradiance (short wave)	0.82 Langley/min
Surface temperature	24.0°C (derived in model)
Surface reflectivity	0.25 (estimated from data)
Surface roughness	0.0 (default)
Surface particle reflectance	1.0 (default)

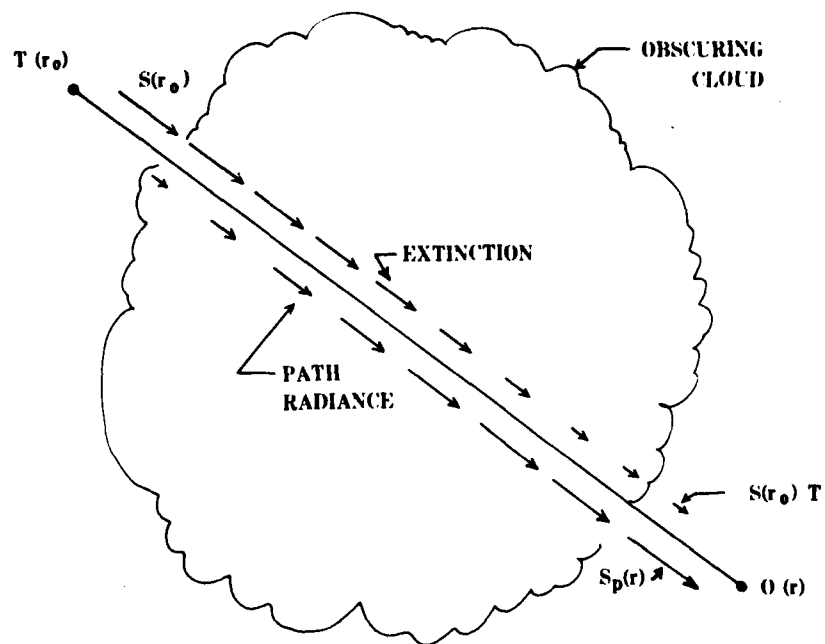


Figure 1. Sketch demonstrating the effects of extinction and path radiance on radiant energy received by an observer.

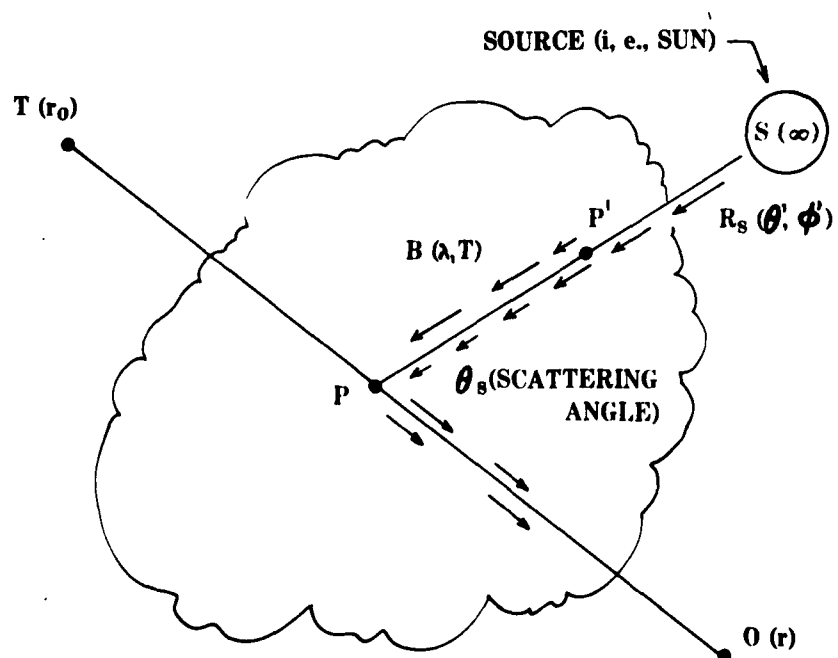


Figure 2. Sketch demonstrating the scattering of ambient radiation into the LOS.

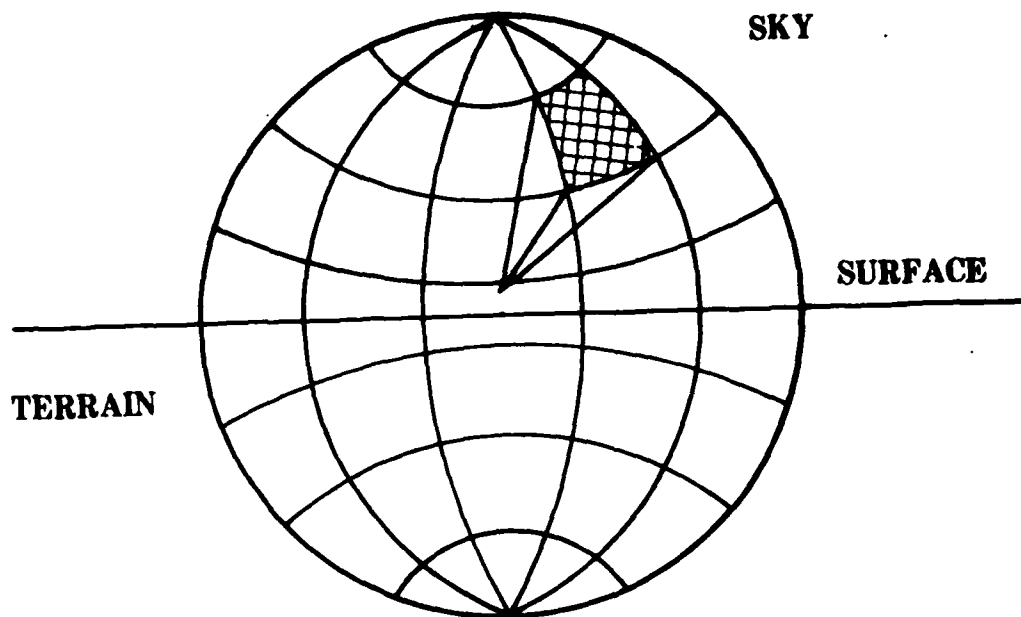


Figure 3. Sketch demonstrating the sky/terrain sectoring scheme used in the model.

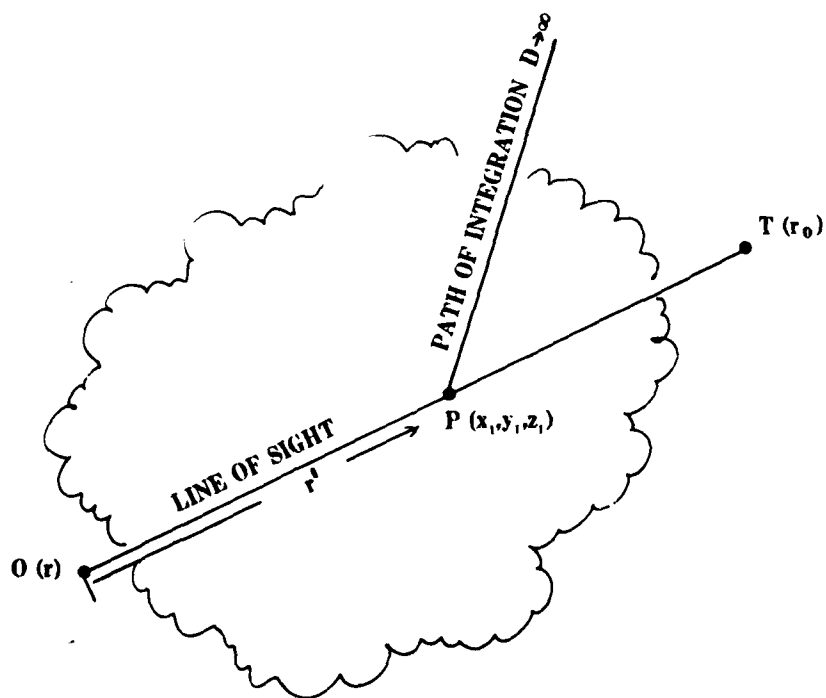


Figure 4. Sketch demonstrating the geometry for computing optical thickness.

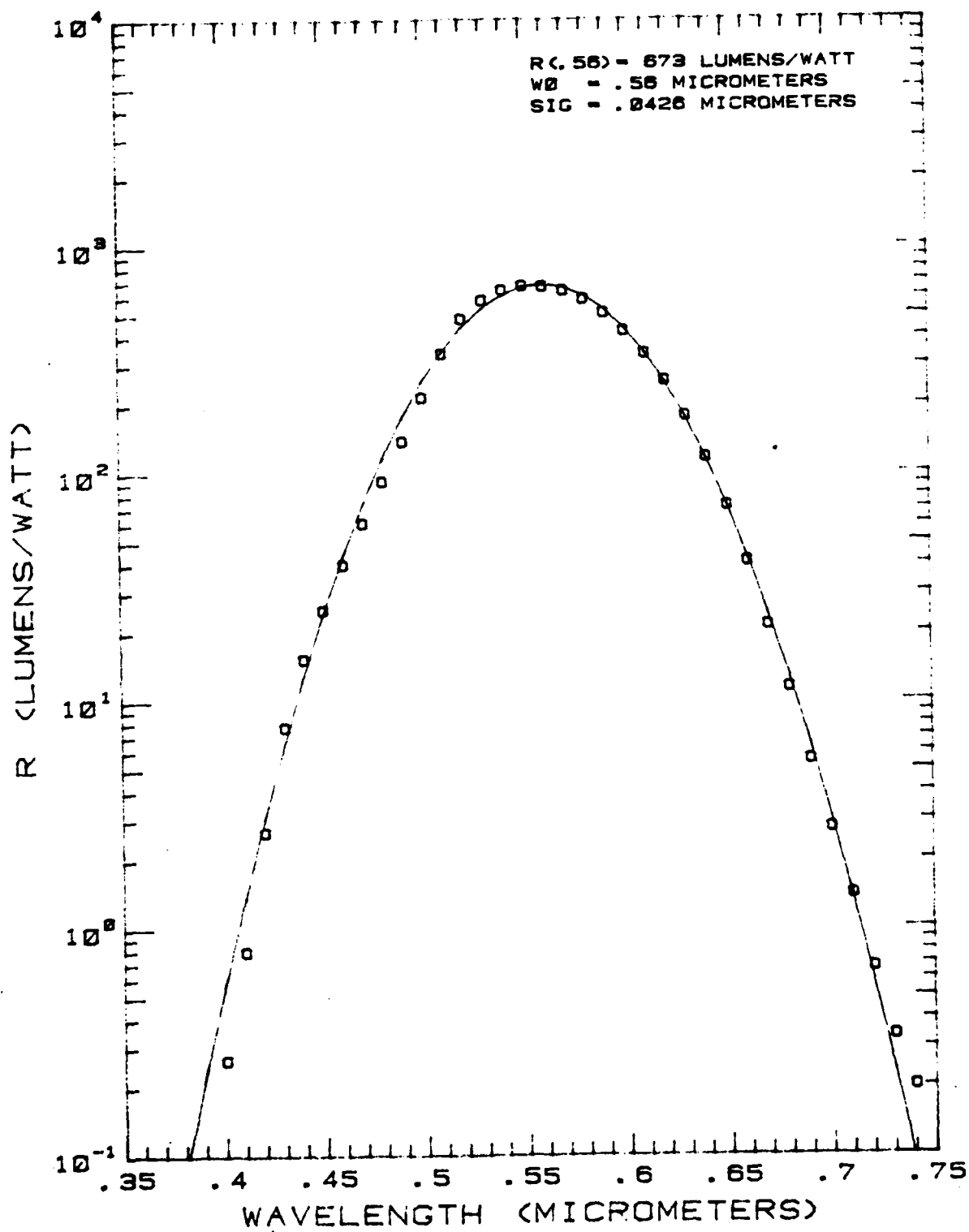


Figure 5. Photopic response curve and Gaussian functional fit for converting radiance ( $\text{W/m}^2$ ) to luminance ( $\text{candies/m}^2$ ).

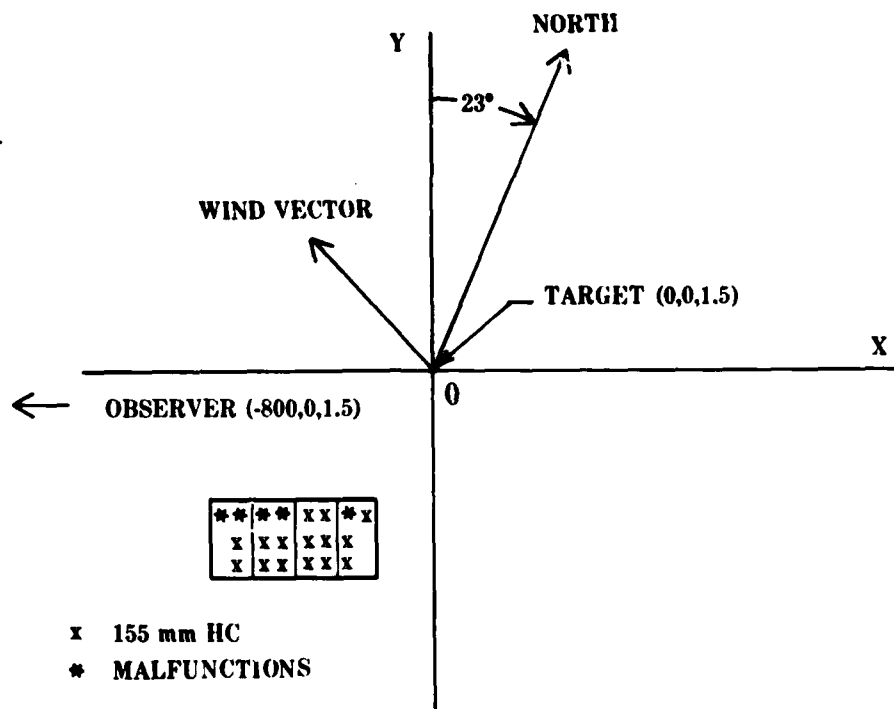


Figure 6. Test configuration for Smoke Week II, Trial 1 Field Test.

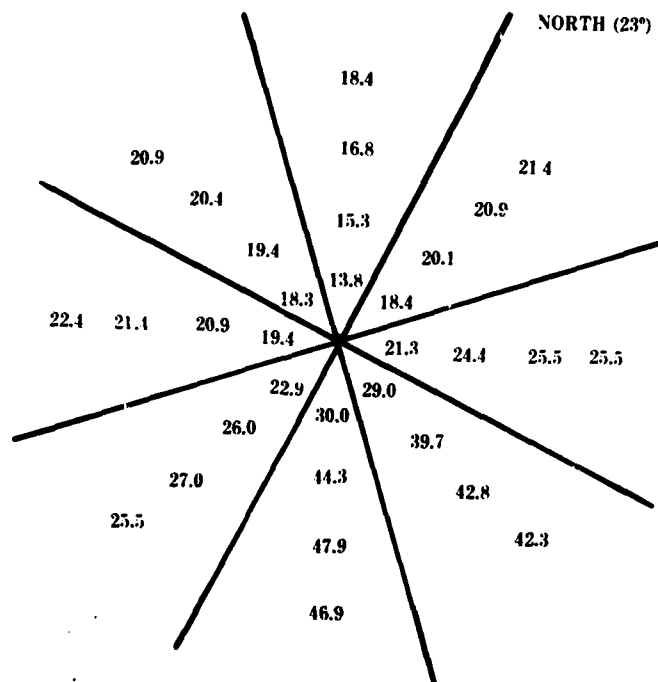


Figure 7. Sky radiance map  $W/(sr \cdot m^2)$  as derived from Smoke Week II, Trial 1 Field Test.

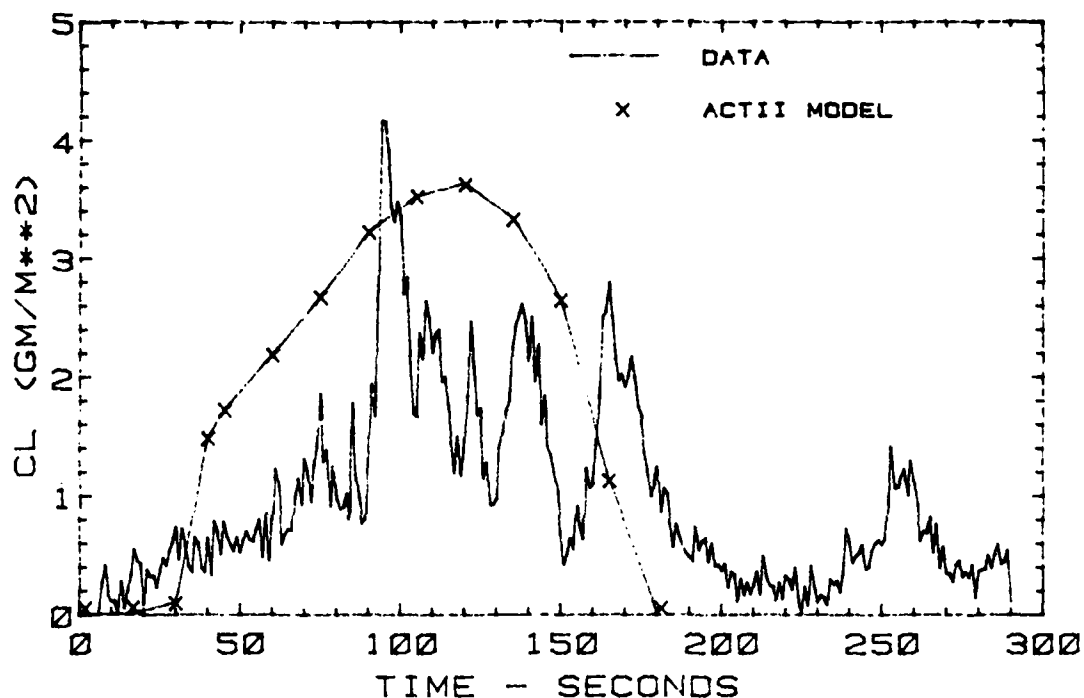


FIGURE 8a. TRIAL 01 SMOKE WEEK II  
Results of comparisons of path integrated concentration

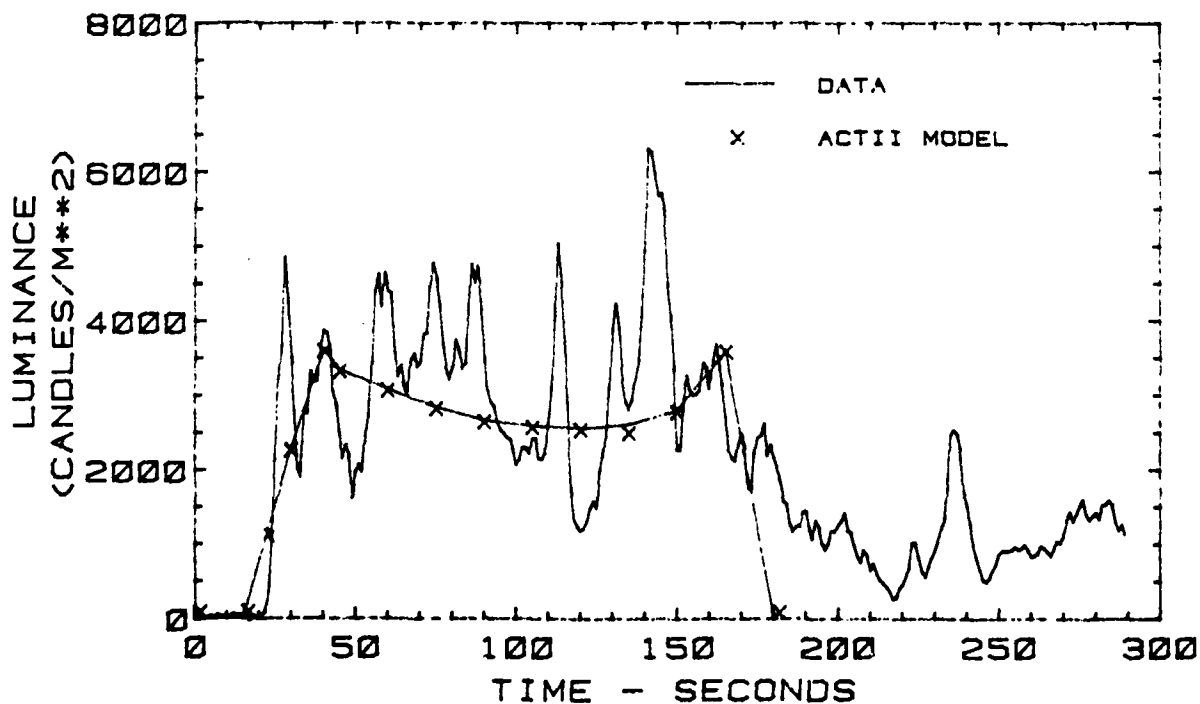


FIGURE 8b. TRIAL 01 SMOKE WEEK II  
Results of comparisons for path brightness

Figure 8. Model comparisons of path integrated concentration (CL) and path luminance with data from Smoke Week II, Trial 1 Field Test.

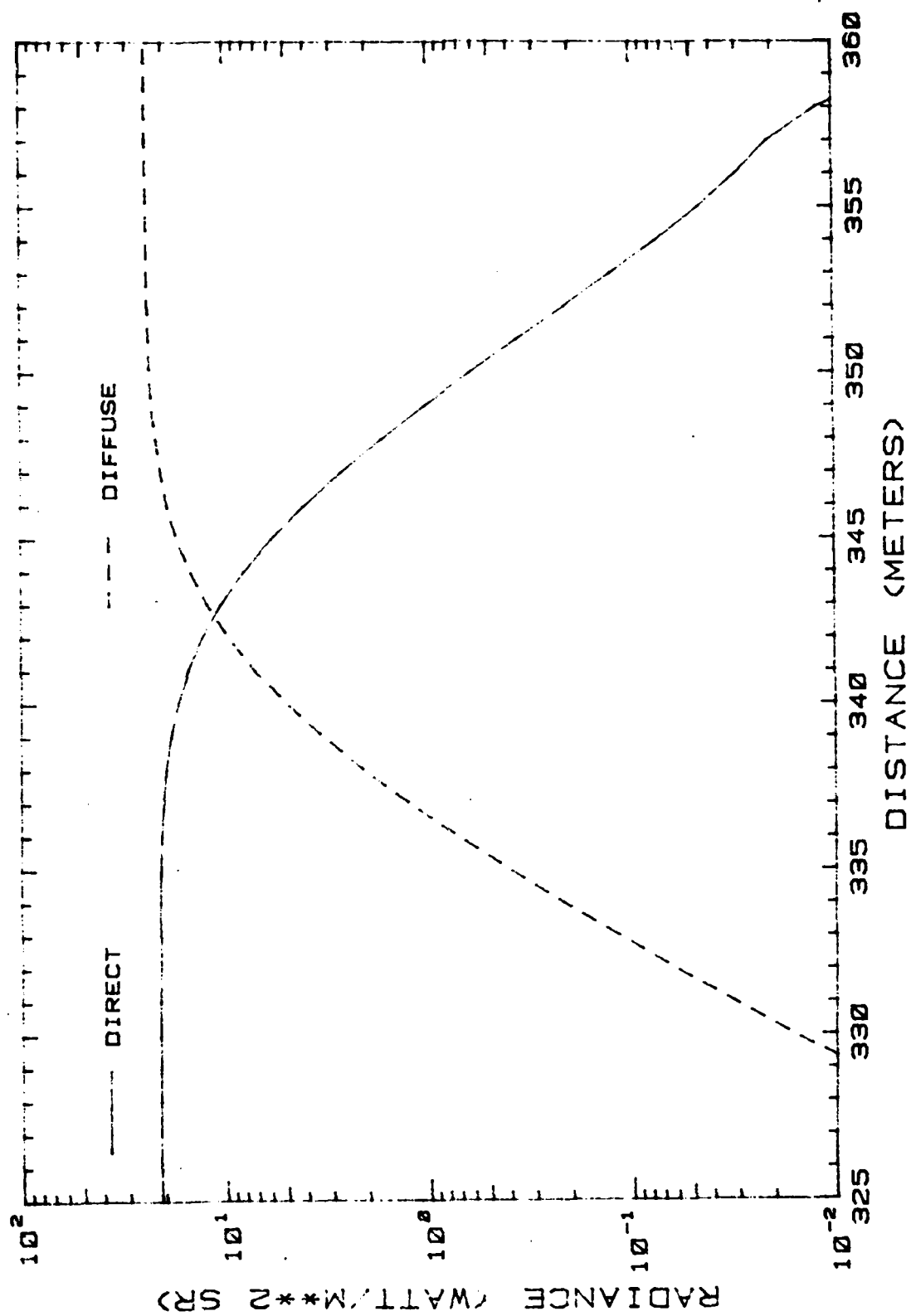


Figure 9. Modeled diffuse and direct radiation as a function of target position along the LOS.

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